The Influence of Breaking at the Ocean Surface on Oceanic Radiance and Imaging

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LONG-TERM GOALS

The long-term goals of the work are to measure the influence of surface wave breaking on imaging across the surface and develop measurements and models of breaking statistics as input to the interpretation and modeling of oceanic radiance measurements.

OBJECTIVES

Image transmission across breaking surfaces will be measured in both the laboratory and the field. Field measurements of breaking and breaking statistics will be used to quantify the degradation and recovery of image fidelity by surface and subsurface processes associated with breaking, including surface turbulence and bubble entrainment. The PI will collaborate with other PIs in the use of breaking measurements and models to interpret measurements and develop models of oceanic radiance and through-surface imaging.

APPROACH

The transmission of light across the ocean surface, whether downwelling or upwelling, depends strongly on refraction across the air-sea interface. Models of refractive effects depend on the structure of the surface; ideally, the surface displacement and all its spatial and temporal derivatives. However, measuring the surface and its derivatives at all relevant scales is technically not possible at present as the spatial scales range from millimeters to kilometers, and the temporal scales from milliseconds to hours. The task is simplified if the temporal and spatial scales can be related through the dispersion relationship for linear surface waves, $\sigma = \sigma(k)$, where σ is the radian frequency, and $k = |\mathbf{k}|$ is the magnitude of the wavenumber vector; but this only works if the wave slope, $ak << 1$ (linear waves), whereas more generally $\sigma = \sigma(k; ak)$. The most important departures from the linear assumption occur in the neighborhood of breaking waves of all scales, from long large gravity waves, to the much smaller, but just as steep, gravity-capillary waves. In the context of ocean optics, the fact that breaking occurs near the crests of the larger waves gives combinations of large surface displacements and large

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slopes, which can lead to significant departures from the simplest horizontal planar-surface assumption that leads to a simple Snell's cone. Breaking also leads to surface turbulence, which does not have a dispersion relationship, and therefore no explicit deterministic relationship between the length and time scales of the surface. At the larger scales, breaking also leads to significant air entrainment and the attenuation and scattering of light by bubbles. For all these reasons, a better understanding of the occurrence (statistics) and scales of breaking in the context of light transmission across the ocean surface, will lead to improved forward and inverse models of the oceanic radiance distribution. Figure 1 shows a schematic of the major components that were to be deployed as part of the RaDyO field deployments off the coast of California in September, 2008. The centerpiece of the planned experiments will be the direct measurement of imaging through the surface using a subsurface (above-surface) display to generate test patterns and a color video camera above (below) the surface. Additional and concurrent measurements include surface displacement (at various scales) as well as occurrence of breaking and air entrainment using LIDAR acoustic technologies, and underwater stereo-imagery.

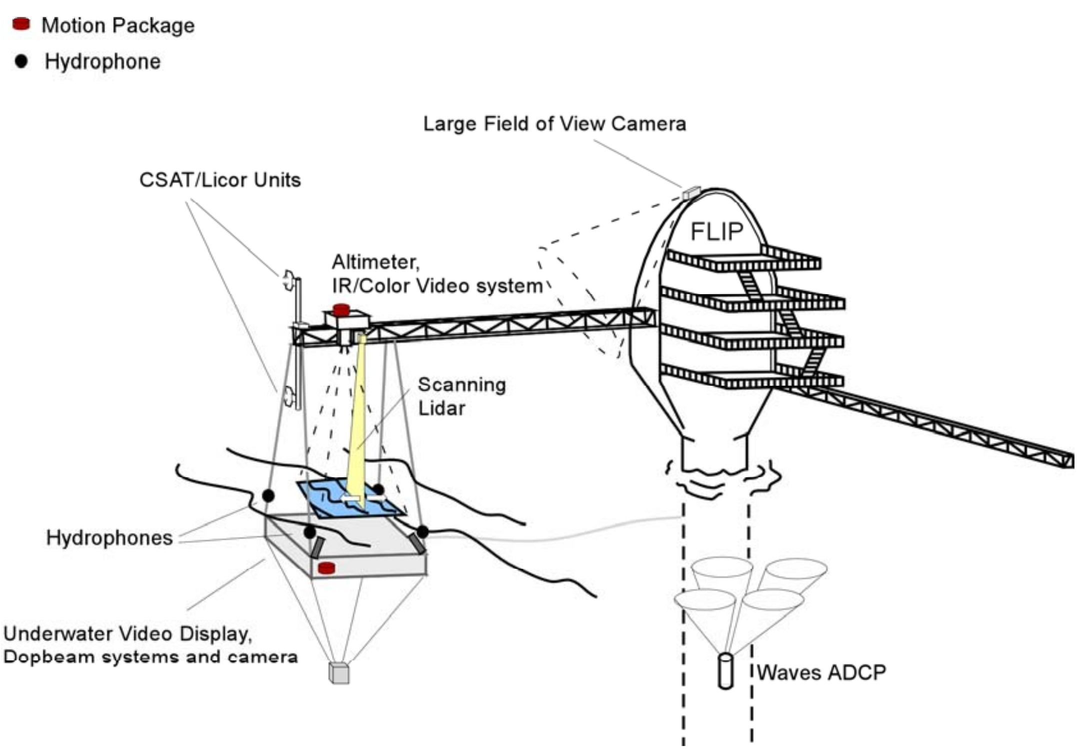


Figure 1: Schematic of the FLIP-based experiments showing the major components of the instrumentation and their deployment.

For imaging through the surface, one of the primary questions concerns the characterization of the fraction of time during which the turbulence and bubbles due to breaking will make any imaging impractical. This requires a statistical description of the probability of breaking over different length and time scales; the characterization of the time scales between breaking at a point; the distance between breaking events at a particular time, and the time scale for the disturbance (turbulence and bubble clouds) to decay to acceptable levels for imaging.

In a seminal paper, Phillips (1985) introduced, $\Lambda(\vec{c})d\vec{c}$, the average length of breaking fronts traveling with velocities in the range $(\vec{c}, \vec{c} + d\vec{c})$. The first moment of the corresponding scalar distribution, $c\Lambda(c)dc$, gives the area per unit area of ocean surface per unit time swept out by breakers traveling in the same speed range. Therefore, $\int_0^\infty c\Lambda(c)dc$ gives the area per unit area per unit time swept out by *all* breakers. If we assume that imaging is impractical during active breaking at a point, this gives a lower estimate of the probability of breaking interfering with imaging during any time interval. Using simple arguments, based on Froude scaling (that the length and time scales are related through the dispersion relationship) it may be shown that the whitecap coverage, the fraction of surface covered by breaking waves, is proportional to the second moment, $\int_0^\infty c^2\Lambda(c)dc$. Similar arguments applied to the depth to which breaking mixes the surface water (and also the small optically-significant bubbles) result in the volume of fluid mixed down by breaking per unit area per unit time being proportional to the third moment, $\int_0^\infty c^3\Lambda(c)dc$. Thus measurements of breaking are fundamental to a determination of the effects of breaking on the transmission of light through the ocean surface and the ability to image through the surface.

WORK COMPLETED

Laboratory Experiments

During 2006-2007 we completed a series of laboratory experiments designed to simulate the effects of wave breaking, entrained air and gravity-capillary waves on the attenuation, scattering and refraction of light transmitted from the atmosphere. The data from those experiments will be compared with field data from the SIO Pier Experiment (see below) measuring the time scales associated with the recovery of through-the-surface images after breaking.

The SIO Pier Experiment

As hosts for the RaDyO SIO pier experiment in January 2008, a significant effort was expended during fall and early winter 2007 to prepare for this three-week experiment. The most visible aspect of this preparation was the design, construction and installation of a new instrument boom on the NW corner of the pier. Along with the original boom on the SW corner of the pier, this provided RaDyO PIs with unprecedented access to incident wind and wave fields from the west. Other aspects of preparation for the pier experiment included the installation of two new lab spaces on the pier, the provision of trailer/office space just east of the entrance to the pier, the provision of logistical support for the shipping and recovery of equipment, and IT infrastructure for all the PIs.

During the pier experiment we deployed a suite of instruments from the SW boom as shown in Figure 2. This system included a comprehensive meteorological package including an eddy momentum and (sensible and latent) heat flux package, passive and active IR system for surface imaging and kinematics, a scanning LIDAR for surface wave measurements and an RGB system for imaging transmissions by a submerged programmable LED display. The latter system provides the analogue of the light source in the laboratory studies conducted in 2006-2007.

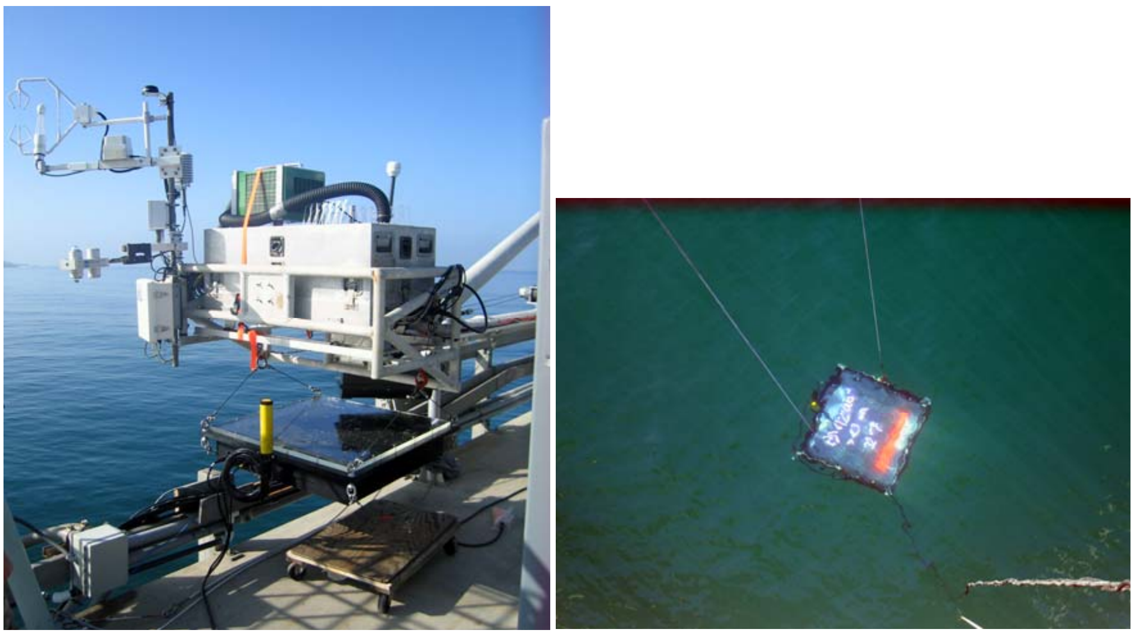


Figure 2: The eddy flux, scanning LIDAR, passive-active imaging system (left) and the subsurface programmable LED display during the SIO Pier experiment, January 2008.

Santa Barbara Channel Experiment

A: Preparation for the RaDyO Community

In 2007 it was agreed that a second boom on the starboard side of FLIP would be needed to accommodate the instrumentation for the Santa Barbara experiment (Fall 2008) and the Hawaii experiment (Summer 2009). The PI arranged for Eric Slater, a retired SIO engineer with many decades experience on FLIP to design and oversee the construction and testing of a new starboard boom for FLIP. Construction and testing of the boom was funded by a grant from ONR that also covered some of the logistical costs of FLIP’s deployment in the Santa Barbara Channel (SBC) Experiment in September, 2008. (N00014-08-1-0383, “Oceanic Radiance and Imaging: FLIP Support for September'08

Experiment”) In addition to overseeing the boom construction, Luc Lenain handled much of the logistical interface between the PIs and FLIP for the SB experiment.

B: This Program

During the course of the year, work proceeded to design, construct and test instrument systems for the SBC Experiment. The systems were an extension of those used in the SIO Pier experiment, supplemented by upper ocean turbulence measurements and the waves ADCP on the hull of FLIP. Following our experience with the motion of the subsurface LED display in the SIO Pier experiment we decided to use it in a complementary mode with the display in the air and a subsurface video camera system was designed and built for imaging the display.

Originally a navy tug had been scheduled to tow and anchor FLIP for the SB Channel experiment; however, the tug was rescheduled for other work in Guam and at the last minute a much smaller commercial tug (the only one available) was hired to do this work. This was not optimal and it was a difficult FLIP deployment after which the port boom was irreparably damaged during its deployment and we were left with just the starboard and face booms. This limited the boom space for instrument deployment by the PIs and time for intermittent measurements from the booms had to be shared between PIs.

Notwithstanding the setback of having only two booms rather than three, a preliminary examination of the data from the experiment suggests that it is a rich data set. Preliminary analysis of the data is shown below.

RESULTS

SIO Pier Experiment

Time series of the meteorological variables during the last two weeks of the SIO Pier experiment are shown in Figure 3. A wide range of wind speeds was encountered from calm winds up to 14 m/s. This provided several excellent examples of transitions from smooth seas to breaking seas which led to transitions in the optical quality of through-the–surface imagery. A particular example of a wind event on January 17, accelerating from approximately 1 m/s to 8 m/s in the course of 15 minutes is shown along with imagery in the visible (RGB) and the IR in figure 4. During the lower wind speed the linear pattern of the LED display is clearly visible. At the higher wind speed the passage of a small breaking wave clearly distorts the transmission making the linear features indistinguishable on the right hand side of the display in the wake of the breaker..

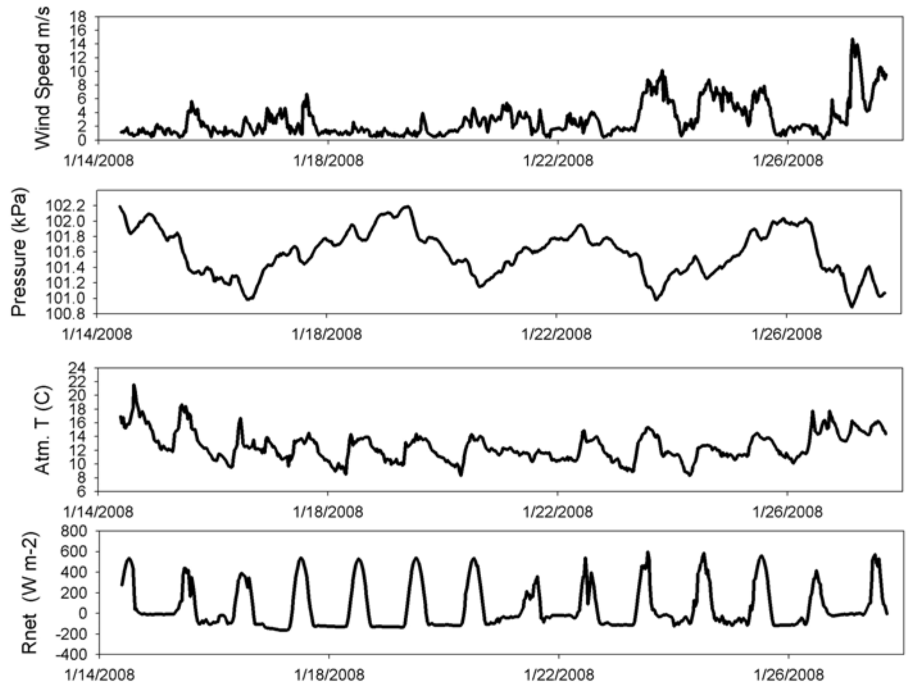


Figure 3: Time series of meteorological parameters during the SIO Pier Experiment, January 2008.

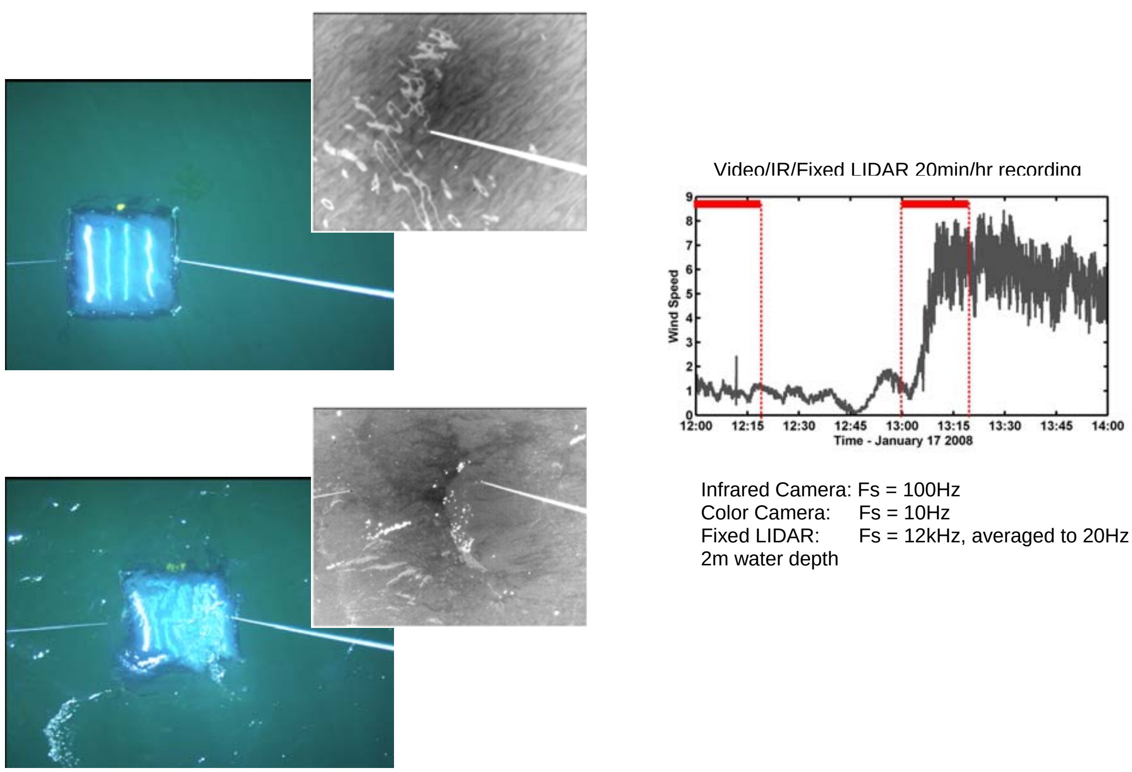


Figure 4: Visible and IR imagery of the subsurface LED display before (above) and after (below) the atmospheric front (right) passed by on January 17.

Figure 5 shows the distribution of pixel intensity during a wave breaking event, on January 17th 2008, at 16:37 (Local time) in the red band of the RGB camera (the pattern was constituted of red and black stripes at this time). The intensity of transmitted light shows the evolution from bimodal to unimodal distributions during breaking, and then a slow recovery to the original bimodal distribution. This is the same qualitative behavior as was seen in the laboratory studies and demonstrates that the duration of image deterioration due to breaking can be quantified. In a practical sense, this is one of the most important metrics of imagery through the surface: the fraction of time the image is degraded by breaking and small scale roughness at the surface.

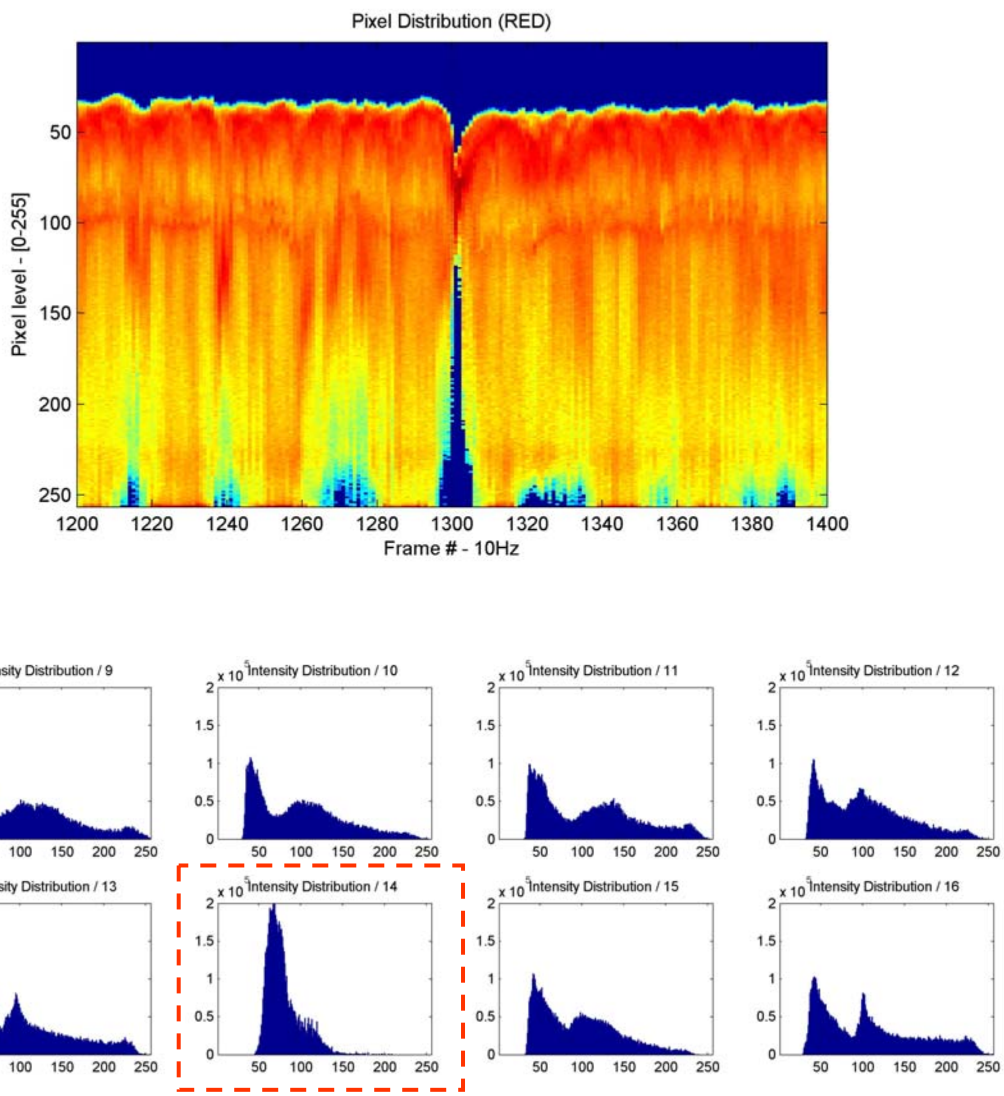


Figure 5: Evolution of the pixel intensity distribution in the red channel going from bimodal to unimodal to bimodal, before during and after a breaking event passes across the surface. This can be compared with qualitatively similar results in the laboratory.

Santa Barbara Channel Experiment
Figure 6 shows FLIP as deployed with the working starboard and face booms and the damaged port boom lashed to the hull.

Figure 7 shows a diagram and list of the instrumentation deployed on the port boom and details of some of the instrumentation.

Figure 8 shows spectrograms of the wave field and a time series of the wind field going from calm to a maximum of 12 m/s during the course of the experiment. Note the strong diurnal sea breeze during much of the experiment. This is very advantageous for studying the variation of the optical transmission across the surface over a wide range of conditions.

Figure 6: R/P FLIP deployed in the Santa Barbara Channel in September 2008.

Figure 9 shows data from the scanning LIDAR giving a spatio-temporal cross-section of the surface along the line of the scan. This will permit excellent determinations of the sea surface slope at horizontal scales of O(0.05 – 10) m. Also shown is a time series of surface displacement at a horizontal position in the line scan.

Finally, Figure 10 shows the set up of the stereo system on the starboard boom, a pair of stereo images and the corresponding reconstruction of the surface. The stereo imagery along with the closer calibration of the scanning LIDAR will permit accurate stereo imagery reconstruction of the surface, and the wave slope statistics for input to optical transmission models.

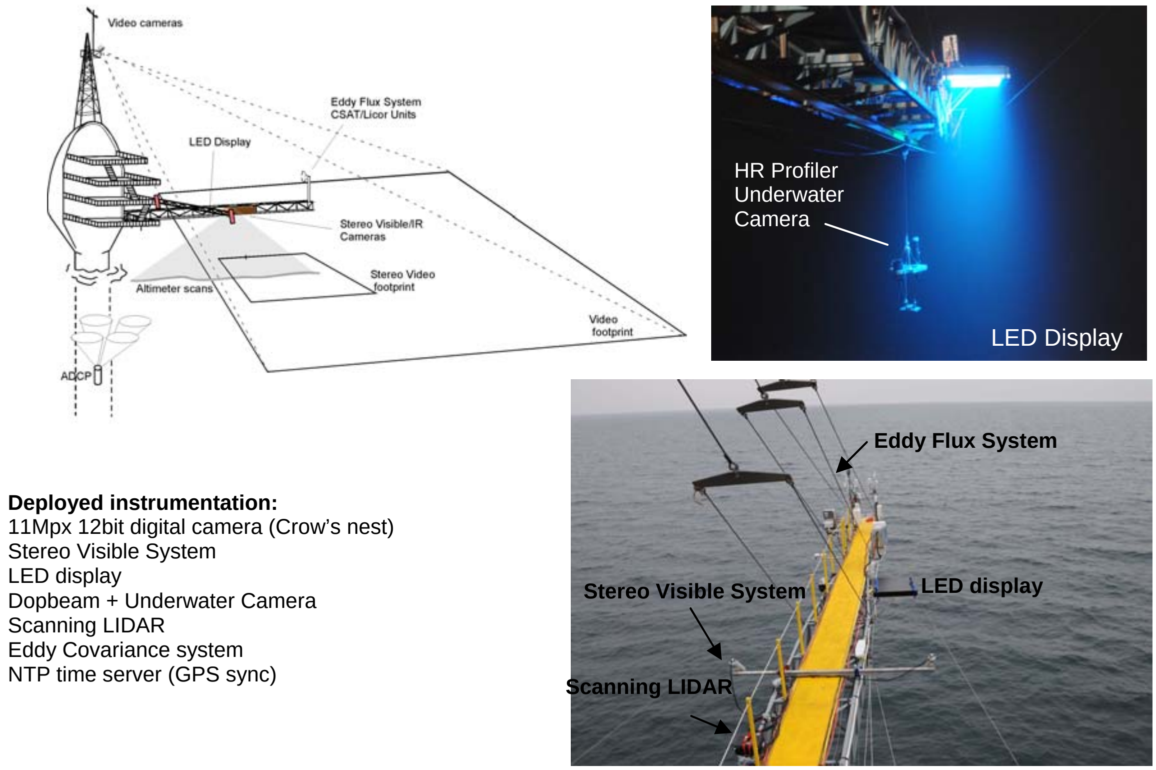


Figure 7: Deployed instrumentation during the Santa Barbara Channel Experiment in September 2008, with photographic detail of instruments on the new starboard boom.

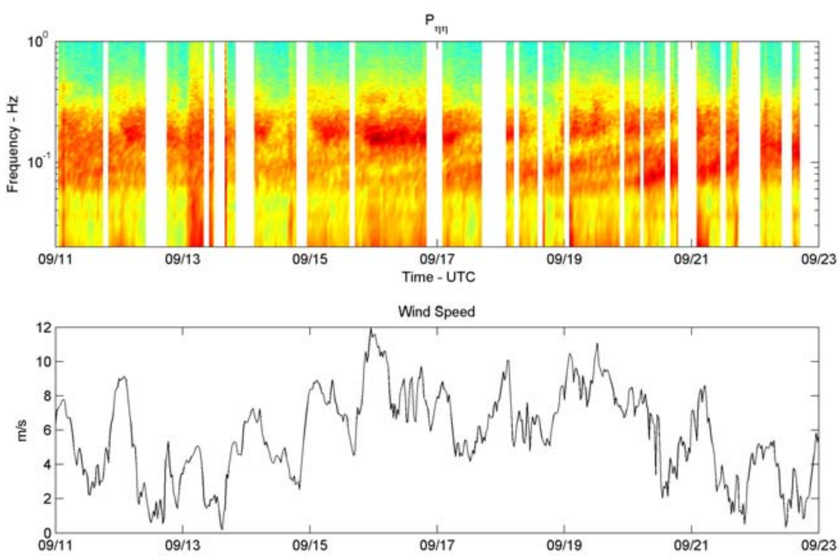
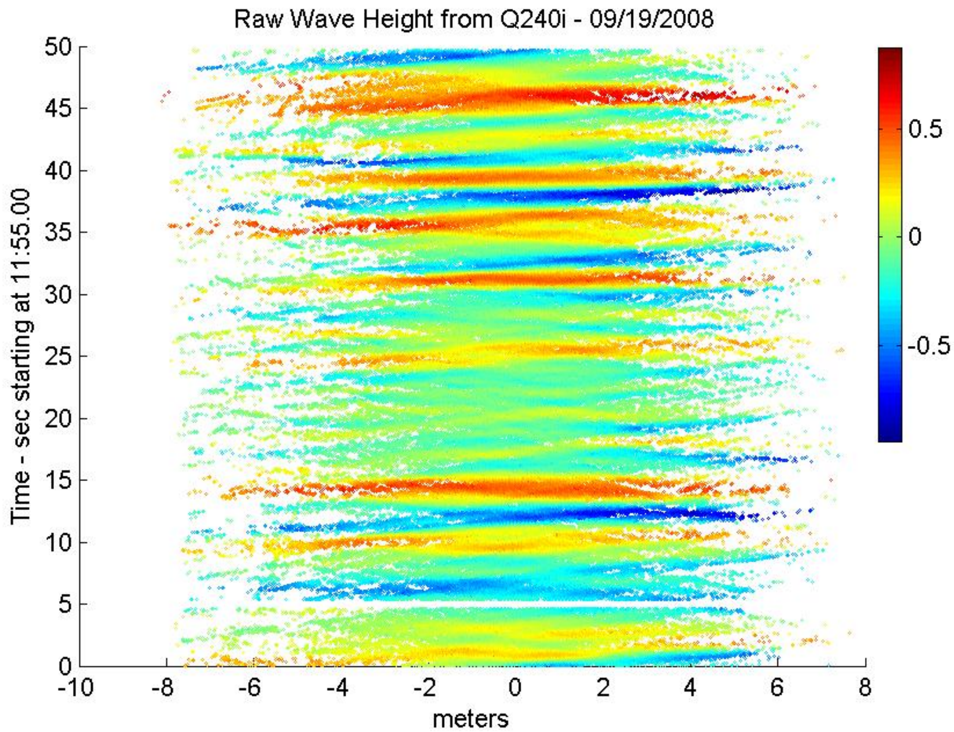


Figure 8: (Top) Surface wave displacement frequency spectrogram measured from the Scanning Laser Altimeter. Only data in the 10x10cm footprint below the instrument is considered and (bottom) wind speed measured by the ultrasonic anemometer (30min average)

(a)



(b)

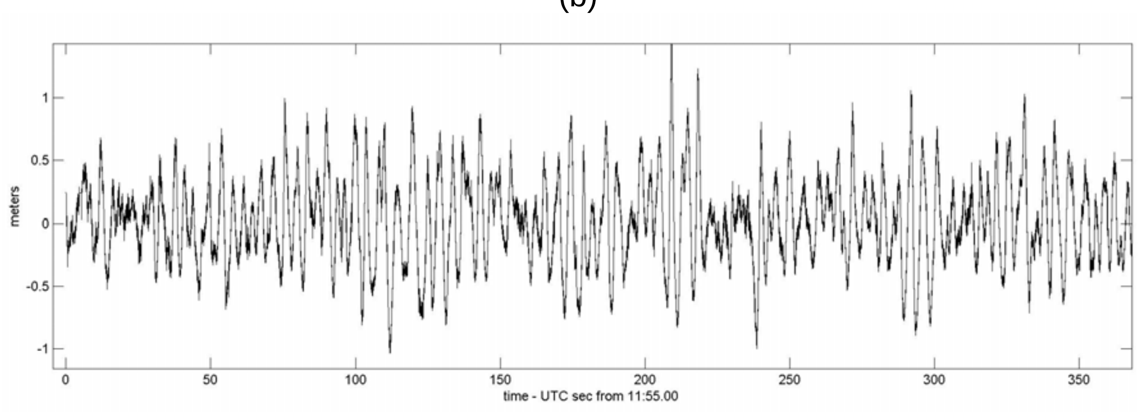


Figure 9: (a) Spatio-temporal display of surface wave displacement measured by scanning LIDAR at 30 lines/second, and (b) time series of displacement taken on September 19 2008 starting at 11:55.00 UTC.

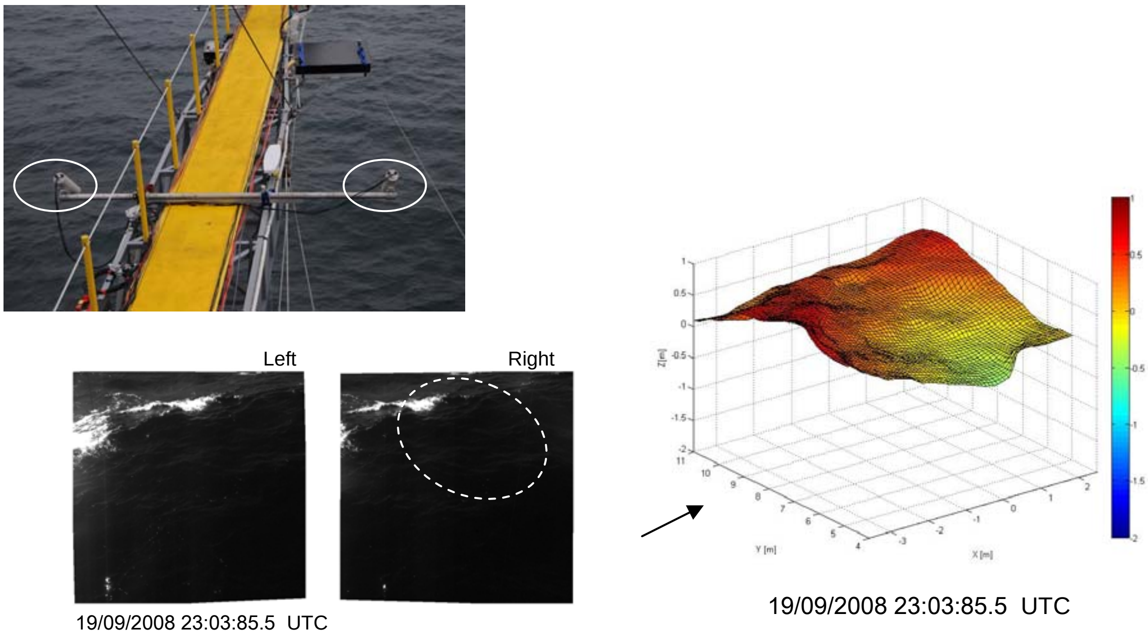


Figure 10: Stereo imagery from the starboard boom during the Santa Barbara Channel Experiment. A pair of images and its corresponding reconstruction is shown.

IMPACT/APPLICATIONS

It is too soon for there to be any impact or applications of this work beyond the RaDyO program.

RELATED PROJECTS

Construction and testing of the new starboard boom was funded by a grant from ONR that also covered some of the logistical costs of FLIP's deployment in the Santa Barbara Channel Experiment in September, 2008. (N00014-08-1-0383, "Oceanic Radiance and Imaging: FLIP Support for September'08 Experiment")

REFERENCES

Phillips, O.M. Spectral and statistical properties of the equilibrium range in wind-generated gravity waves. *J. Fluid Mech.*,156, 505-31, 1985.

PATENTS

None

HONORS/AWARDS/PRIZES

None